Superparameterization of Oceanic Boundary Layer Transport

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Award #: N000140610289

LONG-TERM GOALS

To achieve deeper understanding of physical processes in turbulent planetary boundary layers and apply it to the development of more physically accurate modeling of coherent vortices to assess the oceanic boundary layer parameterizations used in high-resolution ocean models, specifically with respect to their impact on synoptic model predictions.

OBJECTIVES

One of the most difficult processes which limit our ability to generate realistic, high-resolution simulations of the ocean state is intermittent nature of oceanic turbulence related to the presence of coherent structures at wide range of scales when simple parameterizations based on eddy diffusion concepts do not necessarily provide the correct answer. The coherent vortices have life-times in excess of the appropriate eddy turnover time. This clearly contradicts the notion underlying the dimensional analysis of the turbulent cascade. It is necessary first to understand the transport of momentum and heat due to coherent vortices in order to properly parameterize it in ocean circulation models. That is a main goal of our study.

APPROACH

An interactive approach of data analysis and modeling is pursued. The data analysis provides a detailed description of the currents in the boundary layer, and guides the model development; the model on the other hand is intended to isolate and elucidate essential physics governing the flow behavior, thus aiding the interpretation of the observational data.

WORK COMPLETED

A dominant-mode model has been designed to explicitly simulate coherent roll vortices and their interaction with the mean flow. It was used for initialization of boundary layer model developed by Ginis et al. (2004) and generalized to include the Coriolis force. Transport properties of roll vortices were calculated and compared with the results of LES simulations. New physical mechanisms important for prediction of baroclinic eddies in sheared background flow and parameterization of submesoscale processes were investigated (Sutyrin 2007a, Carton and Sutyrin 2007). An effective

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
30 SEP 2007	**Annual**	**00-00-2007 to 00-00-2007**

4. TITLE AND SUBTITLE	
Superparameterization Of Oceanic Boundary Layer Transport	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **University of Rhode Island,Graduate School of Oceanography,Narragansett,RI,02882**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S)
	11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
code 1 only

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**Same as Report (SAR)**	**7**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

quasi-Lagrangian approach was developed for analysis of ageostrophic pulsations of stratified lens-like eddies (Sutyrin 2007b).

RESULTS

a) *Transport properties of roll vortices in the boundary layer.*

We used the boundary layer model developed by Ginis et al. (2004) which is designed to explicitly simulate roll vortices and their interaction with the mean flow. Since this model has been originally designed for the boundary layer in non-rotating fluid, it was modified to include the Coriolis force for planetary boundary layer simulations. That model assumes that a) the roll vortices extended along the direction of the background wind; b) the spatial scale of the roll vortices along x-axis and in the vertical is much smaller that the spatial scale along y-axis. These differences in the characteristic spatial scales allow for splitting the full 3-D system of equations into two subsystems for the mean flow variables and for the deviations. Concerning the spatial structure of the rolls, note that we do not assume that the lengths of roll vortices are of the same scale as the distance between the convective cross-sections, any subgrid scale parameterization (it is the main concept of the parameterizability) is based on the assumption that the statistical characteristics of subgrid scale motions (in our case, the roll vortices) are fully determined by the large scale environment (the resolved scales). The statistical properties of subgrid scale motions are dependent on the spatial scales of the mean flow. In each cross-section the roll vortices have the properties corresponding to the large-scale forcing within the area of the cross-section.

The model is calibrated using the available data on the structure of the planetary boundary layer. An example of the vertical velocity snapshot is shown in Fig. 1 which is agrees well with the results of a dominant-mode model based on a single horizontal mode (Fig. 2). We presently conduct numerical experiments to study formation, orientation and scale selection of roll vortices in a prescribed synoptic field and to assess existing parameterization methods.

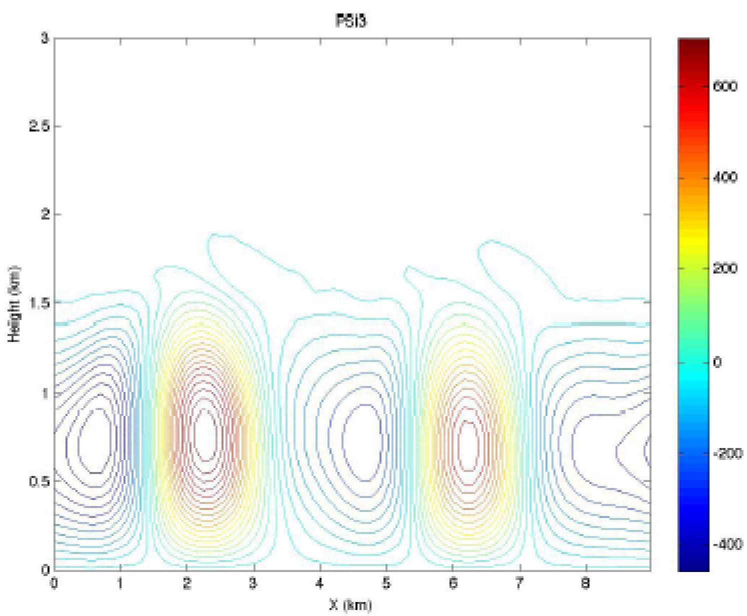

Fig. Convective 2D streamfunction in the planetary boundary layer model for explicit simulations of rolls vortices used in this study.

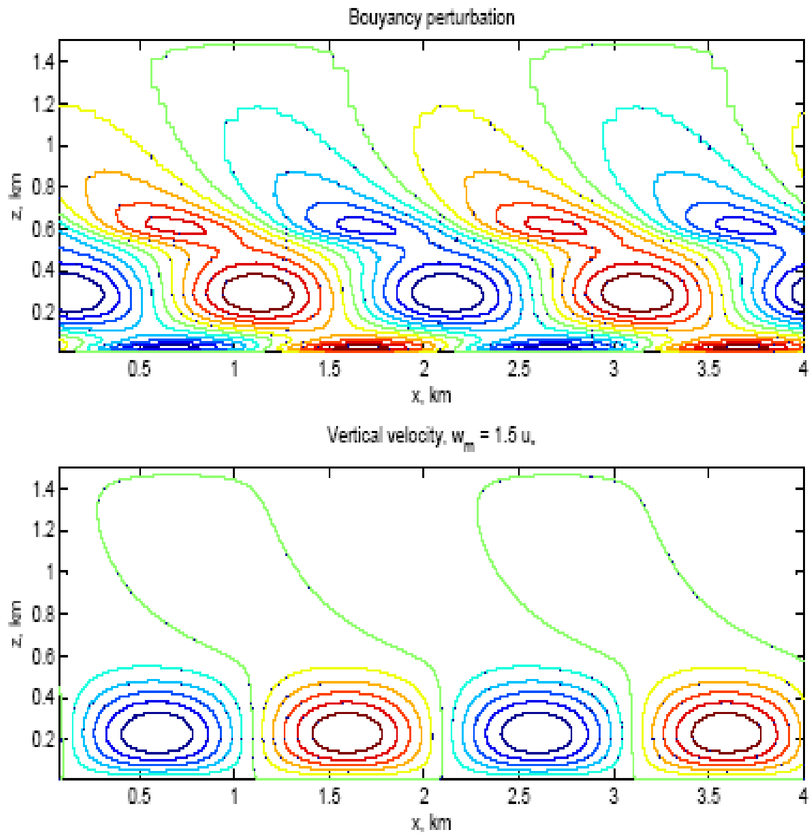

Fig. 2 The bouyancy distribution (upper panel) and vertical velocity (lower panel) in the dominant-mode PBL model based on a single horizontal mode.

b) Modeling ageostrophic instabilities in vertically sheared flow over a sloping bottom

A multi-layer ageostrophic version of Phillips' model over sloping topography with small variations of the layer thickness was analyzed to describe different types of instability (Kelvin-Helmholtz, Rossby-Kelvin, baroclinic) in horizontally uniform flows. The dispersion curves for the Rossby waves and inertia-gravity waves are investigated for two-and-half layer configuration to identify instabilities occurs if there is a pair of wave components which have almost the same Doppler-shifted frequency related to crossover of the branches when the Froude number increases (Fig. 3). Simple criteria for Rossby-Kelvin-type ageostrophic instabilities are found which exactly correspond to violation of sufficient conditions for the flow stability (Ripa 1991). In both cases the growth rate (and the interval of unstable wavenumbers in the vicinity of the resonant wavenumber) are shown to be proportional to the square root of the corresponding gradient of the layer thickness.

As mentioned by Sakai (1989), ageostrophic instabilities in horizontally sheared flows can be interpreted in the present context by resonance between different Rossby, inertia-gravity, and trapped Kelvin modes. In such cases, the waves interact horizontally in contrast to the vertical interaction in the Rossby-Kelvin instability discussed above. However, even for the order one Rossby number, the growth rates of ageostrophic instabilities in horizontally sheared flows are typically quite small (less than 5% of the Coriolis parameter)

The dispersion curves demonstrate that Rossby-Kelvin types of ageostrophic instability related to the thickness gradient in different layers can coexist together (and with Kelvin-Helmholtz instability) and their growth rates may exceed the growth rates of conventional baroclinic instability (figure 3). Nevertheless, the growth rates of Rossby-Kelvin instabilities are within 10% of the Coriolis parameter that are much smaller than the growth rates of Kelvin-Helmholtz instability and their intervals of unstable wavenumbers are much narrower. Such inefficiency of resonances between the Rossby and inertia-gravity waves modes to generate substantial unbalanced motions in varying baroclinic flows is consistent with the small-Rossby-number
asymptotic analysis and with astonishing persistent of balance demonstrated in a number of previous studies.

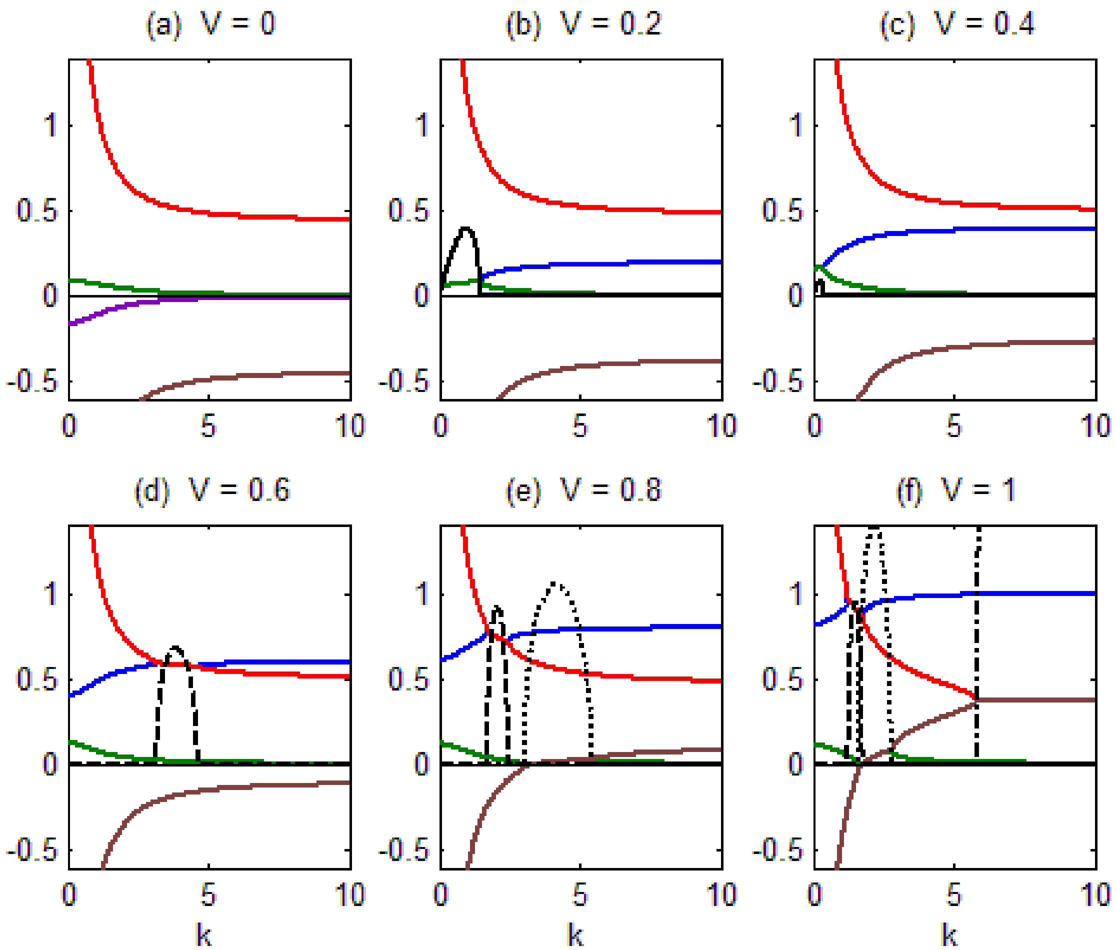

Fig. 3 The real part of the phase velocity for the second mode of inertia-gravity waves (red and brown curves)and the Rossby wave modes (blue and green curves) depending on the wavenumber **k** ***for six values of the Froude number V. The growth rates (multiplied by 10) corresponding to crossover of the branches are shown forthe baroclinic instability (solid line at (b) and (c)); Rossby-Kelvin instability (dashed and dotted lines at (d), (e), (f)) and Kelvin-Helmholtz instability (dash-dotted line at (f)).***

c) The effects of sheared flow on an intense baroclinic vortex

The motion of a localized vortex on the beta-plane in the presence of a horizontally and vertically sheared flow is analyzed by an asymptotic theory and numerical simulations (Sutyrin and Carton 2006). Vortex drift due to the background potential vorticity gradient dominates the advective effect of the vertically sheared flow on the vortex. Additionally horizontally sheared flow modifies the vortex drift due to nonlinear interaction of the azimuthal modes one and two (Sutyrin and Carton 2007). These effects can explain observed propagation of warm-core rings in regions of the Northeastern Atlantic Ocean far from topographic obstacles where satellite data are available with a good space and time resolution.

d) Ageostrophic pulsations of lens-like stratified axisymmetric vortices

Exact analytic nonlinear solutions for finite-area lens-like anticyclonic vortices pulsating with inertial frequency (pulsons) were recently described in a self-similar form (Sutyrin 2006). All pulson solutions have linear profile of radial velocity which is not affected by horizontal friction. An initial value problem was considered using Lagrangian variables for stratified axisymmetric flows in isopycnal coordinates (Sutyrin 2007b). If the initial radial velocity deviates from the linear profile, inertia-gravity waves propagate towards the edge of the vortex and form shocks calculated by a simple numerical model. After shocks dissipate, the solution tends to the non-stationary self-similar pulson solution with linear radial velocity. The ability of lens-like vortices to support inertial pulsations may be relevant to observed dominance of near-inertial oscillations in the oceanic gravity wave band. In particular, properties of inertia-gravity waves and enhanced mixing observed inside the core of warm-core Gulf Stream ring (Kunze et al. 1995) can be explained by existence of inertial pulsations in such lens-like anticyclonic vortices.

IMPACT/APPLICATION

A new way to assess the effects of planetary boundary layer parameterization based on explicit simulation roll vortices and their interaction with the mean flow (superparameterization) should provide more realistic modeling of oceanic variability. The means by which we have analyzed ageostrophic pulsations and evolution of baroclinic eddies over topography and in sheared flows in this study are novel and useful for future investigations.

RELATED PROJECTS

New knowledge about the behavior of roll vortices in strong wind conditions gained from this study is being incorporated into a coupled hurricane-ocean model under NOAA and NSF projects by Isaac Ginis. The explicit simulation of coherent vortical structures is used by Prof. J.C. McWilliams for parameterization of Langmuir circulations in the upper ocean.

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